Meta-analytic findings reveal lower means but higher variances in visuo-spatial ability in dyslexia

Abstract

Conflicting empirical and theoretical accounts suggest that dyslexia is associated with either average, enhanced, or impoverished high-level visuo-spatial processing relative to controls. Such heterogeneous results could be due to the presence of wider variability in dyslexic samples, which is unlikely to be identified at the single study level, due to lack of power. To address this, the current study reports a meta-analysis of means and variances in high-level visuo-spatial ability in 909 non-dyslexic and 956 dyslexic individuals. The findings suggest that dyslexia is associated not only with a lower mean performance on visuo-spatial tasks, but also with greater variability in performance. Through novel meta-analytic techniques, we demonstrate a negative effect size for mean differences (-.457), but a positive effect size for SD differences (+.118; SD ratio = 1.107). In doing so, this is the first study to demonstrate impoverished visuospatial processing of the majority of individuals with dyslexia in addition to greater variance in performance in this group. The findings advocate for further consideration of both the presence of, and reasons for, increased variance in perception, attention and memory across neurodevelopmental disorders.

Keywords: Dyslexia, meta-analysis of variance, visuo-spatial ability

Introduction

According to the the *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; *DSM–5*; American Psychiatric Association), dyslexia is a 'a pattern of learning difficulties characterized by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities'(p. 67, 2013), prevalent in roughly 7-10% of the population (Gilger, Allen, & Castillo, 2016). Whilst the characterization of dyslexia as a deficit of word decoding and phonological processing is rarely disputed, a tension arises when the impact of dyslexia on nonverbal processing is considered. Theoretical accounts posit impairments in aspects of spatial and perceptual processing as either a cause or consequence of dyslexia (Gilger et al., 2016; Goswami, 2015), whereas the empirical evidence for such deficits is mixed.

A great deal of focus has been placed upon providing putative low-level visual explanations for reading and writing problems associated with dyslexia. The most prominent theory to have arisen out of this line of research is the magnocellular theory which posits that abnormalities in the dorsal visual pathway are the primary cause of the disorder (Stein & Walsh, 1997), although the validity of this hypothesis is still under considerable discussion. In support of the magnocellular theory, in some studies dyslexic readers have shown relatively poor performance on tasks tapping into the perception of motion, low-spatial frequency visual information and high frequency temporal information (Borsting et al., 1996; Galaburda & Livingstone, 1993; Graves, Frerichs, & Cook, 1999; Iles, Walsh, & Richardson, 2000; Ramus, 2004; Slaghuis & Ryan, 1999; Stein, 2001; Stein & Walsh, 1997; Talcott et al., 1998). In addition to putative dorsal stream dysfunction, some lines of evidence have suggested that individuals with dyslexia show reduced visual attentional span (Bosse, Tainturier, & Valdois, 2007; Lobier, Zoubrinetzky, & Valdois, 2012; Valdois, Bosse, & Tainturier, 2004) and difficulty orienting spatial attention effectively (Facoetti et al., 2003, 2006; Facoetti, Paganoni, & Lorusso, 2000; Facoetti & Molteni, 2001). A recent review of the literature suggested that the deficits in magnocellular and attentional functioning in dyslexic readers seem to be the consequence of lower levels of reading experience rather than an abnormality of dorsal steam development (Goswami, 2015; Joo, Donnelly, & Yeatman, 2017; Olulade, Napoliello, & Eden, 2013). Corroboratively, study designs which have matched the reading age of dyslexic and control samples have produced less conclusive data (Fernandes, Vale, Martins, Morais, & Kolinsky, 2014; Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Valdois, Lassus-Sangosse, & Lobier, 2012; Ziegler, Pech-Georgel, Dufau, & Grainger, 2009). Thus, the direction of cause and effect between low-level visuospatial deficits and dyslexia remains unclear.

By contrast, some researchers speculate that individuals with dyslexia may have special talents in visuospatial ability in general (Craggs, Sanchez, Kibby, Gilger, & Hynd, 2006; Miles, 1993; West, 1997), or in a particular subset of visuospatial tasks (Brunswick, Martin, & Marzano, 2010; von Karolyi, 2001; von Károlyi, Winner, Gray, & Sherman, 2003).The Geschwind-Galaburda hypothesis suggests that this enhancement is related to the predominantly left hemispheric pathology seen in dyslexia, leading to enhanced functioning of the non-pathological right hemisphere (Geschwind & Galaburda, 1987), although the Geschwind-Galaburda hypothesis has been criticized on many grounds (Bryden, McManus, & Bulman-Fleming, 1994; McManus & Bryden, 1991). In support of this Bacon and Handley (2010) found that individual differences in visual memory predicted reasoning ability in people with dyslexia but not in individuals without dyslexia, suggesting that they develop modes of reasoning that depend on visual rather than verbal representation. In addition, von Károlyi (2001) and von Károlyi et al. (2003) found that dyslexic readers were faster than controls at identifying whether line drawings depicted possible or impossible objects, implying that they develop enhanced global visual integration abilities. Both Winner et al. (2001) and Duranovic et al. (2015) conducted relatively large and extensive studies of visuospatial skills in groups of dyslexic and non-dyslexic adults and found that the former group performed worse on many of the tasks, including those implicating mental imagery and visual memory. However, they suggested that these impaired readers may yet show enhancements on 'real-world' tasks that tap into everyday visual problem solving. In support of this, Attree et al. (2009) found that dyslexic readers performed better than controls on a spatial layout memory task following exploration of a virtual environment. Similarly, Brunswick et al. (2010) found that on tests of everyday visual knowledge, and when navigating a virtual environment, dyslexic readers performed better than controls but this effect was gender-specific; only dyslexic men performed better than non-dyslexic men. This has been linked to men's use of non-verbal strategies to solve problems; women who adopt non-verbal strategies perform with similar levels of accuracy to men (Lehmann, 2000; Peters et al., 1995).

While several meta-analyses exploring the neuroscientific and behavioral bases of dyslexia have been conducted previously (Benassi, Simonelli, Giovagnoli, & Bolzani, 2010; Linkersdörfer, Lonnemann, Lindberg, Hasselhorn, & Fiebach, 2012; Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Richlan, Kronbichler, & Wimmer, 2009, 2013; Swanson, Xinhua Zheng, & Jerman, 2009), there have been few attempts to collate evidence for higher-level visuospatial functioning in dyslexia as a means of addressing what drives these heterogeneous research findings. The only existing meta-analysis on this topic selected dyslexic children between 8-12 years of age (Tafti, Boyle, & Crawford, 2014). The authors assessed 12 studies involving visuospatial deficits in a total of 324 dyslexic children and 304 controls. Those with dyslexia performed worse on visuospatial tasks, representing an average effect size across all tasks of .72, with deficits focused in the visual attentional and magnocellular domains, but effect sizes varied greatly by task type. In addition, a recent review summarized evidence for differences between individuals with reading disabilities (RD) and those without on a range of spatial processing tasks (Gilger et al., 2016). They found no significant differences in performance between dyslexic and control readers in 72% of tasks within a selection of 21 research papers. In 17% of the tasks reviewed, the RD group performed significantly worse than controls, and in 11% of tasks the performance of the RD group was superior to that of the control group. The most consistent dyslexic disadvantage was seen on tasks measuring spatial rotation ability, while a dyslexic advantage was most commonly seen on tasks measuring holistic visual processing and perceptual closure, such as the impossible figures test (von Károlyi, 2001; von Károlyi et al., 2003).

In summary, there appears to be a mixed body of evidence in relation to potential visuospatial enhancements or deficits in dyslexia. The heterogeneity of these findings likely comes from two sources: heterogeneity of the participant samples and heterogeneity of tasks used in the studies (Gilger et al., 2016). For example, under Goswami's (2015) interpretation, it is more likely that visuospatial deficits in dyslexia will be seen in later years, once the accumulation of impoverished reading experience has had an impact on dorsal stream and attentional functioning. This would lead to group differences in older but not younger participant samples. However, no existing meta-analysis or review quantitatively addresses this potential difference. The meta-analysis performed by Tafti et al. (2014) was limited by its focus on a very tight age range of participants but a relatively large spread of tasks selected in a small set of published studies. The review by Gilger et al. (2016) only provides a very broad quantitative overview of potential deficits and enhancements of dyslexic readers while advocating that moderating factors such as age should be addressed in ongoing research.

An alternative way to account for the inconclusive results regarding visuospatial processing in dyslexia would be to posit that there exist subsets of people with dyslexia who have extremely enhanced or impoverished visuospatial processing abilities, arising from greater variance in dyslexic samples. Winner et al. (2001) acknowledged this possibility in a previous study stating that, 'It is possible that there is a spatial advantage in dyslexia but that this advantage shows up only in the right tail of the distribution (as does the male advantage in math).' (p.108). The notion of increased variance in one subpopulation has been most notably employed in the study of sex differences in intelligence and mathematical ability (Arden & Plomin, 2006; Halpern et al., 2007; Hyde & Mertz, 2009; Irwing & Lynn, 2005), leading some authors to claim that, 'a small difference in variance [between males and females] may have consequences at the extremes of ability resulting in visibly unequal numbers of one sex among the less able or among the elite' (Arden & Plomin, 2006, p.46). The comparison of group variability may be particularly relevant when one of the groups is determined by psychopathology which often comes hand in hand with compensation strategies and/or comorbidity. In support, work investigating differences in variance between clinical and control groups has reported both higher intra and inter variability in performance indicators like attentional allocation and focus in ADHD (Antonini, Narad, Langberg, & Epstein, 2013; Kofler et al., 2013, 2014; Kofler, Rapport, & Matt Alderson, 2008; Rapport et al., 2009), higher neural variability and noise in Autism Spectrum disorder (Dakin & Frith, 2005; Dinstein et al., 2012; Haigh, Heeger, Dinstein, Minshew, & Behrmann, 2015; Simmons et al., 2009) and more variable auditory responses to human speech syllables by poor compared with good readers (Hornickel & Kraus, 2013).

Meta-analysis in psychology and other fields typically looks at differences in mean performance, which reflects the fact that most statistical analyses of psychological studies also concentrate on statistical tests such as t-tests which compare means rather than variances (and that is also true of ANOVA, analysis of variance, which despite its name only tests hypotheses about means, albeit by looking at differences in variances within the data). Testing for differences in variance between two groups in individual studies will generally not be straightforward since there is far less power in a typical study to detect differences in standard deviations than to detect differences in means, as Winner et al. (2001) noted. In this meta-analysis, we analysed both differences in mean performance and differences in variability in performance between individuals with and without dyslexia. This enabled us to determine whether people with dyslexia show deficits in the visuospatial domain and whether there is evidence to support the contention that a dyslexic advantage or disadvantage would manifest in the tails of the performance distribution (Winner et al., 2001). As previously outlined, there has been a strong emphasis on low-level magnocellular and visual attentional functioning and the evidence is relatively robust for a deficit in this domain (Goswami, 2015; Tafti et al., 2014). However, the focus of the current study was on relatively higher-level visuospatial abilities (e.g. mid-level vision, visual imagery and visual memory). A similar approach was also taken in a recent review of dynamic and complex spatial reasoning in dyslexia (Gilger et al., 2016), in which the authors reasoned that, ‘While studies of these more basic visual abilities are important, they do not represent the type of skill most often studied and considered as an RD [reading disorder]-related gift or as an explanation for the overrepresentation of successful people with RD in artistic, nonverbal reasoning or creative fields’ (p.57).

In a recent review and empirical study of visuospatial abilities in dyslexia involving 80 dyslexic and non-dyslexic participants, Duranovic et al. (2015) separated visuospatial skills into several subtypes: visual memory, visualization, mental rotation and global visual processing. A recent review by Gilger et al. (2016) also demarcated spatial ability constructs into: spatial visualization, spatial relation/rotation and perceptual closure. Such taxonomies are useful in determining in which areas of visuospatial ability individuals with dyslexia show specific enhancements or deficits. Therefore, motivated by Duranovic et al. (2015) and Gilger et al. (2016), we developed our own taxonomy of visuospatial abilities that separated tasks and studies into three classifications: visual memory, visual imagery and visual perception, which broadly captures the framework of visuospatial processing. Table 1 shows how the various task types are defined and provides representative studies in the meta-analysis which use these tasks. Given that many of the low-level visual processing deficits are associated with representation of the stimulus in perception (e.g. attention and magnocellular functioning), it might be expected that individuals with dyslexia would show a larger relative deficit in perception relative to memory and imagery tasks. Therefore, in addition to evaluating the overall effect size for all visuospatial tasks we also calculated individual effect sizes for the three strands of visuospatial processing included in the meta-analysis. In addition, we evaluated whether covariates such as age, IQ and gender ratio influenced effect size. As previously mentioned, group differences may be driven by studies in which there is a higher ratio of males to females (for example Brunswick et al. (2010) found a male-specific advantage for visuospatial processing) or by those including adults rather than children as the downstream effects of impoverished reading experience may be greater in these participant populations (Gilger et al., 2016; Goswami, 2015). IQ may drive greater variability in the dyslexic sample, in the sense that individuals with dyslexia who have high IQ may develop more sophisticated compensatory strategies engaging visuospatial mechanisms. Analysing the influence of these moderator variables enables us to test whether heterogeneity of the research findings is driven by these factors.

Table 1. Visuospatial task taxonomy used in the meta-analysis and examples of empirical studies that utilized the representative tasks

Category	Subcategory	Representative tasks	Representative empirical study
Memory	Visual short-term	Corsi block span	Bacon et al. (2013)
		Rey Osterrieth immediate	Brunswick et al. (2010)
	Visual long-term	Visual patterns test	Bacon & Handley (2014)
		Rey Osterrieth delayed	Brunswick et al. (2010)
Imagery	Mental rotation	Vandenberg mental rotation	Everatt et al. (1999)
		Mental rotation of pictures	Van Doren et al. (2014)
	Visualisation	Form board task	Winner et al. (2001)
		Paper folding test	Duranovic et al. (2015)
		Cube construction	Everatt et al. (1999)
Perception	Local processing	Block design test	Godoy de Oliveira et al. (2014)
		Embedded figures test	Martinelli & Schembri (2015)
	Perceptual organisation	Picture completion	Godoy de Oliveira et al. (2014)
		Impossible figures	von Károlyi et al. (2003)
		Visual closure test	Germano et al. (2014)

Method

Literature search. To find eligible studies, we conducted both a computerized and manual literature search. In the computerized literature search we explored titles, abstracts, and keywords in several databases (PsychInfo, CrossRef, Web of Science, EBSCOhost) using the following Boolean operation combining two main components pertaining to dyslexia and inclusion of visual or spatial tasks: *DYSLE* AND "VIS*" OR "SPA*"*. We placed no time limit on publication date and some publications were added from the authors' personal collections (RC and NB). As these were broad search terms they captured many potentially relevant articles (see figure 2), the clear majority of which were false alarms. Titles and abstracts were screened with strict inclusion criteria. We included only studies from published journal articles, comparing a group of participants with dyslexia (not reading disabilities) with a group of controls on high-level visuospatial tasks as outlined in table 1. Neuroimaging studies were included only in circumstances when they reported appropriate behavioural data. The selection and exclusion process of all abstracts yielded in the literature search was done by RC and JS. The search yielded 80 articles that were then further scrutinized for validity. After this stage 28 articles were selected for the final meta-analysis. The predominant reasons for exclusion at this stage were that: the tasks included were not sufficiently high-level in visuospatial terms, did not have enough statistical information available, did not have an appropriate pathological or control group or were non-empirical. A visualization of the search process is shown in figure 1.

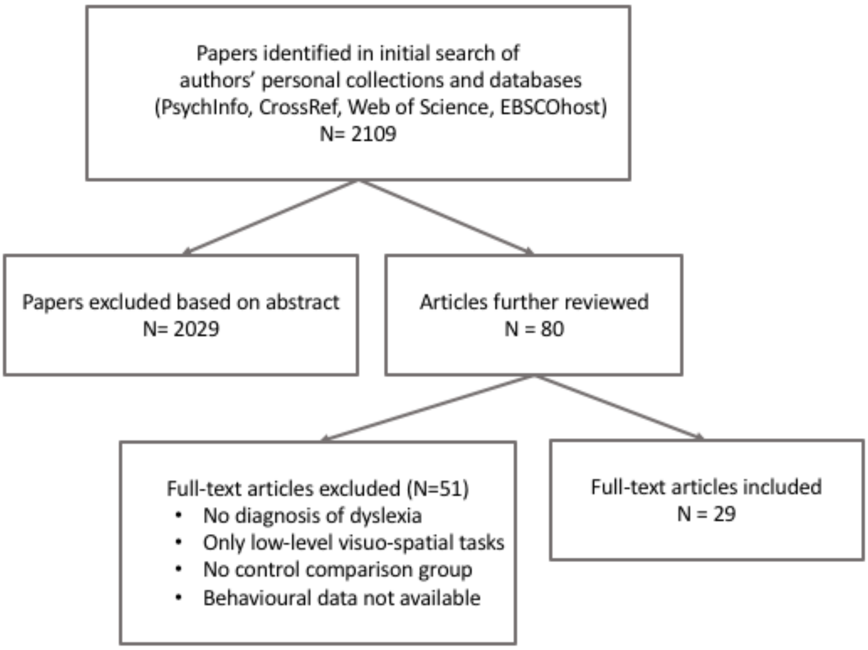

Figure 1. Visualisation of paper search

The selected articles yielded a sample of 909 non-dyslexic and 956 dyslexic participants, with 114 unique effect sizes over 36 unique empirical studies. Studies were coded by XX and XX, with studies coded by one author double-checked by the other author. Data extracted from each study were: the means, m_D and m_C, the standard deviations s_D and s_C, and the sample sizes n_D and n_C for both the dyslexic and control groups. In addition, the articles were coded for the following variables:

1. Mean and SD age of dyslexic and non-dyslexic sample
2. Full-scale IQ of dyslexic and non-dyslexic sample
3. Gender ratio for the dyslexic and non-dyslexic sample
4. Type of task employed (P= Perception; I= Imagery; M= Memory)

Statistical analysis.

Effect size for mean differences. Most meta-analysis uses either Cohen's *d* or Hedge's *g* as an effect size measure, in which the difference between the means is divided by a pooled estimate of the standard deviation, with Hedge's *g* multiplying by a further correction factor (Hedges, 1981). That approach is satisfactory if there are good reasons to believe that s_D and s_C are equivalent. However in the present study we suspected that the SDs were not the same, and therefore it made sense to use Glass's *delta*, calculated as $delta = (m_D - m_C)/\ s_C$. In the few cases where raw standard deviations or means were not available, we used an estimate of a Cohen's *d* effect size calculated from t, F or X^2 statistics (see Lipsey & Wilson, 2001).

Effect sizes for differences of standard deviations. To evaluate effect sizes for group differences in standard deviation, we followed the approach of Nakagawa et al. (2015). They named their estimate of the ratio of standard deviations *VR* (variability ratio), however we found this definition to be confusing as it is similar in name but not in concept to variance ratio, and therefore refer we to it as *SDR*; the ratio of standard deviations. Likewise, although Nakagawa et al refer to Experimental (E) and Control (C) groups, we instead refer to Dyslexic (D) and Control (C) groups. Nagakawa et al.'s equation 9 provides an appropriate effect size measure as:

$$lnSDR = \ln\left(\frac{s_D}{s_C}\right) + \frac{1}{2(n_D - 1)} - \frac{1}{2(n_C - 1)}$$

where *ln()* is $log_e()$, the natural logarithm to base *e*. *lnSDR* has the advantage that equality of standard deviations is indicated by $lnSDR = 0$, and the distribution is unbounded and symmetric around zero. The sampling variance of *lnSDR*, based on Nakagawa et al.'s equation 10, is calculated as:

$$var(lnSDR) = \frac{1}{2(n_D - 1)} + \frac{1}{2(n_C - 1)}$$

Meta-analysis. A problem for meta-analysis in many psychological studies is that each study yields a number of different effect size measures which are not independent. A standard approach for assuring statistical independence is either randomly to choose one effect from each study or to use an averaged effect size for each study. A more robust approach, though, is that adopted by Hedges and colleagues (Hedges, Tipton, & Johnson, 2010; Lipsey & Wilson, 2001) which considers the data as a multi-level model with variance both at the within-study and between-study level. An immediate advantage is that all effect sizes are considered in the modelling. A further advantage is that in meta-regression it is possible to take into account that for some studies there is a within-study comparison (e.g. older and younger participants) whereas other studies consider only older or younger participants (in which case age is a between-study variable).

Publication bias. In any meta-analysis there is always a risk that the studies published in the literature are a biased subset of the studies actually carried out. Two separate ways of assessing this are in common use: the fail-safe N, and funnel plots. Analyses were carried out using the *metafor* library in *R* (Viechtbauer, 2010). For each independent study (in the sense of having independent sets of participants, even if published in the same paper by the same authors) an average effect size was calculated, along with a standard error calculated as the square root of the averaged variances for the effect sizes.

Software. Pre-processing of the data was carried out using *Excel* and *SPSS* v 24.0. The main meta-analysis was carried out in *R* using the *robumeta* package (Fisher & Tipton, 2015). Sensitivity to the different possible values of the *rho* parameter was assessed using the *sensitivity()* function, and in all cases estimates across the range 0 to 1 had minimal effect on the calculations, and therefore the default of *rho = 0.8* was used.

Data availability. The data set analysed during the current study is available as a supplementary file accompanying this manuscript.

Results

Winsorisation of extreme effect sizes. The effect sizes, both for Glass's delta and for lnSDR showed a few cases which were probably extreme, in the sense of being more than 2.5

raw SDs from their mean. The small number of extreme values was handled using the conservative technique of Winsorisation, being replaced by a value 2.5 SDs from the mean. For the 97 estimates of *lnSDR*, there were two extreme values of -3.294 and +5.551, and for the 114 values of Glass's delta there were four extreme values, all negative, with values of -4.88, -3.57, -3.04 and -2.61. The extreme values that were Winsorised are highlighted in Supplementary Table 1.

Summary of meta-analytic approach. Effect sizes could be calculated for 114 results, from 36 independent sets of participants, described in 28 published studies, so that there is clustering of effect sizes within independent sets of participants within separate published studies. We followed the approach of Hedges et al. (2010) who suggested that independent sets of participants within individual published studies were more likely to show similarities, and therefore data were clustered at the level of published studies. Table 2 shows the number of effect sizes and number of studies for each analysis. Means and SDs were available in 97 cases, and for these the corrected Hedge's *g* and Glass's *delta* were calculated. For the remaining 17 results, Cohen's *d* was used as a surrogate for Glass's *delta*, and was calculated from the results of t-tests, F-tests or chi-square tests. *lnSDR* could only be calculated for the 97 effect sizes in which SDs were known (For individual effect size and *lnSDR* estimates see Supplementary Table 1).

Table 2. Number of studies and effect sizes per analysis (perception, memory, imagery)

	All measures	Perception	Memory	Imagery
Analysis of standard deviation differences				
Number of clusters (outcomes)	24 (97)	10 (30)	12 (45)	11 (22)
lnSDR (SE)	.102 (.0366)	.063(.0534)	.114 (.0472)	.153 (.0584)
SDR	1.107	1.065	1.121	1.147
t (df)	t(20.9)=2.80	t(8.72)=1.170	t(10.3)=2.36	t(8.36)=2.63
p	.0108	.271	.0395	.0292
I^2 – see footnote a	44.44	48.33	48.62	25.41
Tau^2 -- see footnote b	.0325	.0376	.0328	0.0174

Analysis of mean differences				
Number of clusters (outcomes)	28 (114)	12 (34)	13 (46)	13 (34)
Glass's delta (SE)	-.457 (.109)	-.389 (.193)	-.391 (.105)	-.706 (.227)
t (df)	-4.19 (26.6)	-2.01 (11)	-3.74 (11.9)	-3.11 (11.9)
p	.000275	.0695	.00287	.0090
I^2 – see footnote a	83.34	84.97	78.17	90.18
Tau^2 -- see footnote b	.4315	.4793	.2546	0.9915

[a] I^2 is a measure of the percentage of variance attributable to study heterogeneity.

[b] Tau^2 is the between-study variance for correlated effects and the between-cluster variance for hierarchical effects.

Meta-analysis of standard deviation differences. The meta-analysis of differences in standard deviations necessarily is prior to the analysis of differences in effect sizes calculated from means, since if there are differences in standard deviation then it is appropriate to use Glass's *delta* for comparing means, rather than Hedge's *g*. Standard deviations were only available for 97 effect sizes. For descriptive purposes figure 2 shows the ratio of the standard deviations in people with dyslexia compared with controls for all 97 results. As can be seen, *lnSDR* is more likely to be positive than negative, 59 values being positive (i.e. $SDR > 1$), 6 being 0 (i.e. $SDR = 1$) and 32 being negative (i.e. $SDR < 1$), with a Winsorised mean of +.110 ($SDR = 1.116$). Simple meta-analysis using *robumeta* gave an estimate for the intercept of *lnSDR* of 0.102 (SE = .0366; t=2.80, 20.9 df, p=.0108), equivalent to $SDR = 1.107$ (see table 2). The SD of participants with dyslexia is therefore significantly higher than that of control participants. A parallel calculation using non-Winsorised values gave a very similar result (estimate of *lnSDR* ntercept = .102 (SE .0383), t=2.66, 21.6 df, p=.0145). Meta-regression was also carried out in *robumeta* to assess whether there were differences between the P, M and I effects. Inclusion of dummy variables for P, M and I did not show evidence of significant differences in *lnSDR*. However, in view of the differences to be described later between P, M and I in Glass's delta we repeated the meta-analyses separately for the P, M and I tasks. As seen in table 1, *lnSDR* was smallest in the P tasks, and not significantly different from zero, it was larger and significant in the M tasks, and it was largest for the I tasks; those trends can be seen in figure 2.

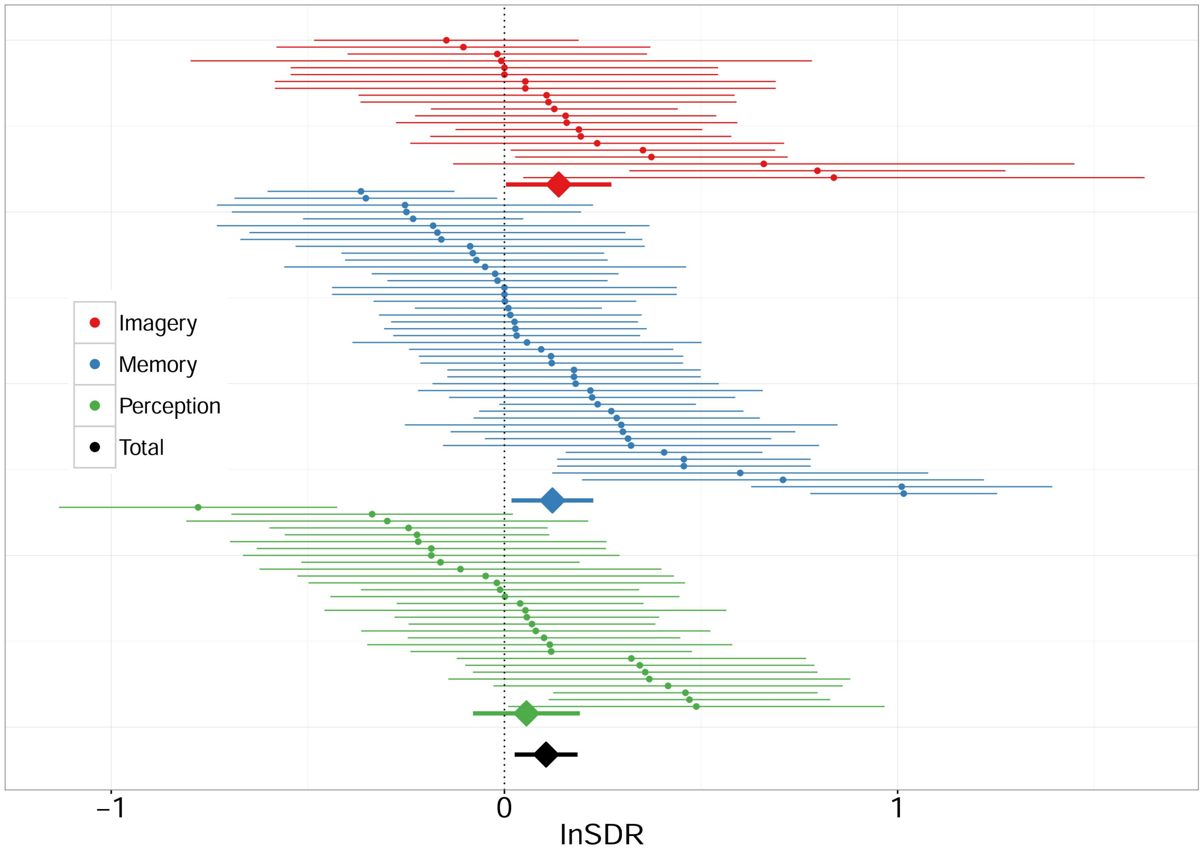

Figure 2. Forest plot of lnSDR for each effect size with 95% CI, sorted by lnSDR magnitude and task type (Imagery/Memory/Perception). Total and task-type meta-regression estimates and their 95% CIs are shown in bold below each task grouping.

Meta-analysis of mean differences. Since the standard deviations of participants with dyslexia and controls are significantly different from each other, the appropriate effect size is therefore Glass's *delta*, Cohen's *d* only being used in the few cases where it is not possible to calculate Glass's *delta* (Ellis, 2010). Figure 3 shows the 114 effect sizes sorted by type of task (I, M and P), and by size within task type. Of the effect sizes, 85 are negative and 29 are positive, the mean effect size being -.457. Simple meta-analysis using *robumeta* gave an estimate of the overall effect of -0.457 (SE .109, t=-4.19, 26.6 df, p=.000275; see table 1). Calculation using the non-Winsorised values gave a very similar result (overall effect = -0.511, t=4.07, 26.8 df, p=.000372). Meta-regressions including dummy variables for task type found significant differences between the types, and exploration including dummies for just I, M or P found that I alone was different to the other task types (t=-2.15, 20.7 df, p=.0434). Separate meta-analyses were therefore calculated for P, M and I tasks, the effect being similar for P (effect = -.389, p=.0695) and M (effect = -.391, p=.0029), and larger for I (effect= -.706, p=.0090). Details are provided in table 2 and the differences in effect size are visible in figure 3.

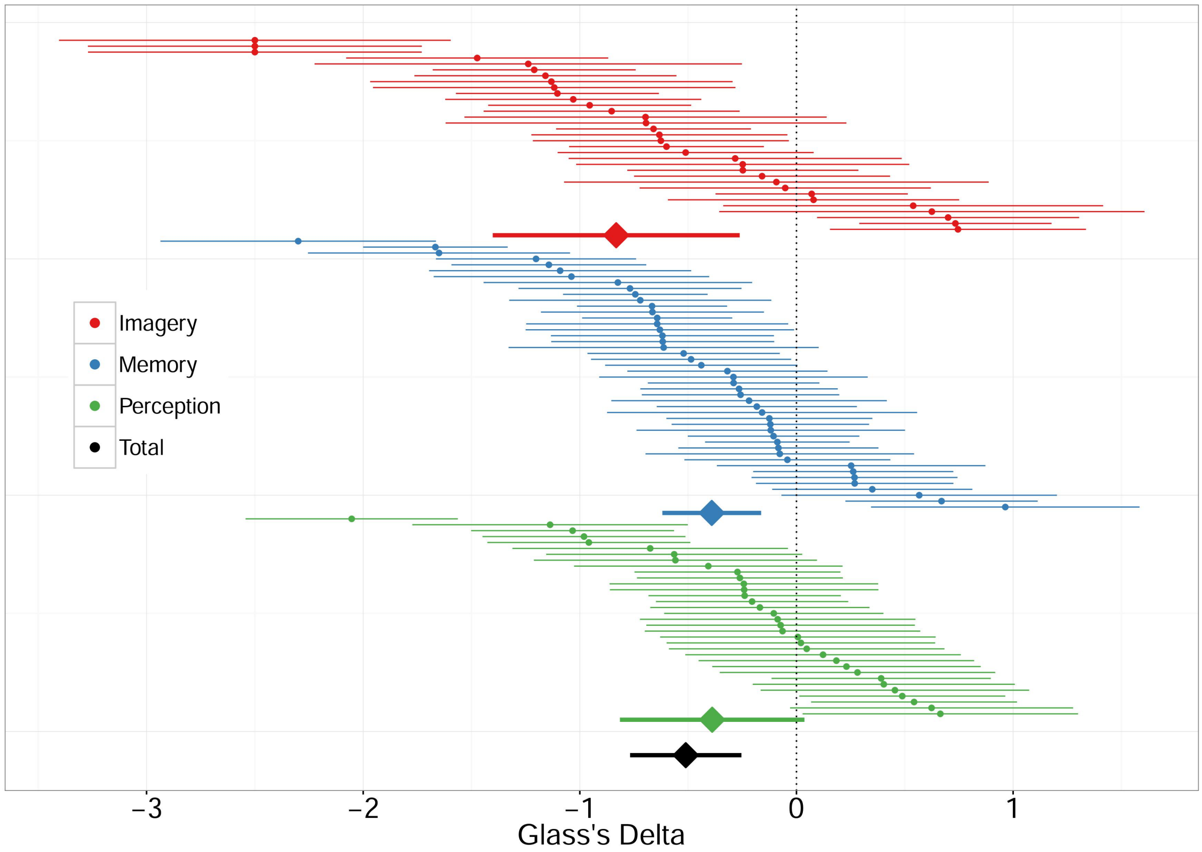

Figure 3. Forest plot of Glass's *delta* sorted by effect size magnitude and task type (Imagery/Memory/Perception)

Moderating variables. Three moderating variables were assessed using *robumeta*, the average age of the participants, the average full-scale IQ, and the ratio of males to females. The ratio of males to females had no significant effect on Glass's *delta* (t=.511, 5.48 df, p=.6290), as neither did average age (t=1.51, 14.6 df, p=.1530), nor IQ (t= .601, 1.67 df, p=.619, but note that *robumeta* advises caution when df < 4). In addition, the size of *lnSDR* was not related to the average age of participants (t=1.508, 11.2 df, p=.159), the sex ratio of participants (t= -0.0222, 4.1 df, p=.769) or the average IQ (t=.241, 1.62 df, p=.836 although see note above about low df in *robumeta*).

Fail-safe N. Rosenthal (1979) introduced the idea of the 'file-drawer problem'; the likely number of studies carried out with non-significant results which were never published and would need to be included in the meta-analysis to nullify the overall effect which was found. If that number is small in relation to the likely number of researchers working on the problem then publication bias is a potential problem. Analyses of the fail-safe N (file-drawer number) were carried out using the *fsn()* function in *metafor*, with results summarised in table 3. For the 35 effect sizes for Glass's delta, assessing a mean difference in the scores of people with dyslexia and controls, the fail-safe N was 1132 using the Rosenthal (1979) method and 811 using the Rosenberg (2005) method. Both numbers are large and it seems unlikely that there is that such a large number of unpublished non-significant studies. For the ratio of standard deviations, *lnSDR*, the fail-safe N is somewhat smaller, being 146 using Rosenthal's method and 121 using Rosenberg's method. The number is still relatively large, particularly as it is far less likely that a study would not be published merely because there was no difference in standard deviations (and indeed, many studies might prefer such a finding, since it fits with the assumption of homogeneity of variances in t-test or ANOVA).

Table 3.

	lnSDR	Glass's delta
Number of independent sets of participants	29	35
File-drawer number		
Fail-safe N (Rosenthal)	146	1132
Fail-safe N (Rosenberg)	121	811
Response bias (Funnel plot)		
Estimated missing studies on right-hand side	8 (SE = 3.35)	0 (SE=3.13)
Regression test for funnel plot asymmetry	z=-0.1882, p=0.851	z= -1.019, p=.308

Funnel plots. Funnel plots assess the possibility that small studies relative to large studies are more likely to be published if they have differences in the expected direction (a lower performance in participants with dyslexia), resulting in asymmetry of the funnel plot. Funnel plots were produced using the *funnel()* function, the number needed to produce symmetry was assessed using *trimfill(),* and Egger's regression test for asymmetry was implemented using the *regtest()* function in *metafor*. Funnel plots for *lnSDR* and Glass's *delta* are shown in figure 4. For Glass's *delta* (figure 4, left), although there is a little asymmetry visible, with four points at lower left, the trim and fill method estimated that there were zero missing studies, and Egger's regression test was non-significant (see table 3). For the *lnSDR* measure (figure 4, right), there is little visible asymmetry, but the trim and fill method suggested there might be eight missing values on the *right* side, with a standard error of 3.35), but Egger's test was non-significant (table 3). The missing values on the trim and fill method are to the right, with the implication that if there are any missing values then they have a higher *lnSDR* than the published study, and hence the meta-analytic estimate of *lnSDR* would be an under-estimate, the difference in standard deviations being somewhat larger than that found in the meta-analysis. Taken overall, the file-drawer and funnel plots suggest that there is little likelihood of publication bias affecting the conclusions of the current meta-analysis.

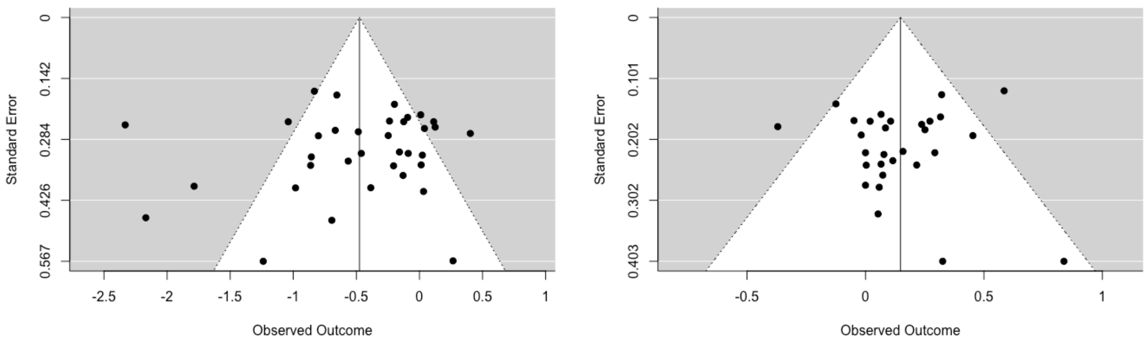

Figure 4. Funnel plots for Glass's *delta* (left) and *lnSDR* (right)

Discussion

This meta-analysis demonstrates that participants with dyslexia perform less well on tests of visuo-spatial ability. The overall estimate of Glass's *delta* was -0.457, which is classified as "medium" in size using the terminology of Cohen (1988). This finding aligns with the majority of studies and reviews in the field (Duranovic et al., 2015; Gilger et al., 2016; Goswami, 2015; Tafti et al., 2014). The current meta-analysis also assessed variability in performance, and finds that participants with dyslexia are more variable, having systematically larger standard deviations than control participants. In addition, we found no influence of moderating variables: age, IQ or gender ratio, on the effect size of group differences in means and variances. Meta-analyses in psychology rarely study differences in the variability of participants, and the present result suggests that this may be a powerful tool for understanding the nature of performance differences between subpopulations. Nevertheless, most individual studies will have little power to detect differences in variance, as can be seen from figure 2, where only about 1 in 5 effects (16/97) has a confidence interval which excludes equality. Meta-analysis avoids this problem by combining many studies, and as a result produces a more powerful study with better generalisability.

Our meta-analysis also suggests there are differences between different types of measure of visuo-spatial ability with larger effect sizes (and SDs) for Imagery and Memory tasks and the smallest effect sizes (and SDs) for Perceptual tasks. Although on average participants with dyslexia show poorer visuospatial ability for all three subdomains, their wider distribution means that participants with dyslexia should become relatively more prevalent at higher and lower visuo-spatial abilities. Evidence, albeit largely anecdotal, suggests that there may be an overrepresentation of individuals with dyslexia in higher educational settings requiring visuospatial and creative skills such as art and design (Bacon & Bennett, 2013; Wolff & Lundberg, 2002). Under models of intelligence (Ackerman, 1996) and expertise (Hambrick, Macnamara, Campitelli, Ullén, & Mosing, 2016) it is highly likely that high visuospatial ability is a necessary (albeit not sufficient) condition for excellence in these domains. Indeed, research suggests that enhanced perception, imagery and visual memory correlate with success at art school and with professional art practice (e.g. Chamberlain & Wagemans, 2015; Kozbelt, 2001; Perdreau & Cavanagh, 2015). While data are sparse on the actual levels of dyslexia in professional practices such as visual art and architecture, it can be speculated that an increased variance in visuo-spatial performance may account for putative overrepresentation of dyslexic students in art and design institutions (Winner et al., 2001). However, it should be noted that this account depends on the distribution of dyslexic performance being normal and crucially symmetrical. It was not possible to consider potential skew of data in dyslexic and non-dyslexic subgroups in the current study, as this information was not systematically reported in the target studies. It would be extremely useful in future for data reporting protocols to include estimates of skew in both clinical and non-clinical populations such that more systematic analyses of normality of group distributions can be undertaken, or for full raw datasets to be made available such that estimations of skew can be calculated. With the addition of further data on the normality of distributions of dyslexic performance and the prevalence of dyslexic individuals in art and design institutions, it would be possible to explore the validity of such claims.

Although aimed specifically at the issue of the mixed evidence regarding talents and deficits in dyslexia, more generally our work raises the possibility that sub-populations of people with particular phenotypes or syndromes may differ from control populations not only in their mean scores but also in their variability. The assumption of equal variances in subgroups such as participants with dyslexia is probably incorrect, and it may well also be incorrect in other psychological domains, in which Cohen's *d*/Hedge's *g* tend to be used uncritically in meta-analysis without testing the key assumption of equality of standard deviations. The logic of Glass's *delta* is, as Ellis (2010) states, 'that the standard deviation of the control group is untainted by the effects of the treatment and will therefore more closely reflect the population standard deviation' (p.10) and it is for that reason that it was used in a previous study of ours concerning the neuropsychological effects of organophosphate pesticides (Ross, McManus, Harrison, & Mason, 2013). The current meta-analysis focused on relatively high-level visuospatial processing, as this was suggested the most likely source of talent in a subset of dyslexic individuals (Gilger et al., 2016). However, there is no reason to believe that increased variance is limited to the tasks studied here. The source of variance may come from more fundamental aspects of perceptual and attentional processing, and therefore it would be of value to conduct similar meta-analyses of variance for performance on magnocellular and attentional tasks in individuals with dyslexia and controls.

The current meta-analysis cannot determine why or how variability in dyslexia is higher than in the general population. It can be speculated that a source of variance exists in the dyslexic group in addition to that found in control populations, which is added to normal variation (the origin of which is probably also not well understood). In the left-hand region of the distribution this could be due to comorbidity of dyslexia with other pathologies such as dyscalculia and ADHD (Eden & Vaidya, 2008; Gilger & Kaplan, 2001; Greven, Harlaar, Dale, & Plomin, 2011; Willcutt et al., 2013; Wilson et al., 2015), while compensation strategies may account for variance in the right-hand region of the distribution. A putative 'unique spatial neurology' in those with reading disorder might result in wider variation in the neurological framework upon which those with dyslexia rely to perform visuospatial tasks in later life (Gilger et al., 2016; Gilger, Talavage, & Olulade, 2013; Gilger & Olulade, 2013). Such variance in differentiation might arise from the reorganization of neural networks in response to both prenatal or developmental disruption in typical verbal processing, resulting in increased variance at the neural as well as the behavioural level. In a recent review of the role of neural variability in clinical pathology, Dinstein, Heeger and Behrmann (2015) suggested that, 'individuals with autism, dyslexia, ADHD, and schizophrenia, but not OCD, exhibit distinct forms of excessive neural variability in comparison to control individuals' (p. 324). In support of this, there is evidence to suggest that dyslexic readers show differential patterns of brain activation while performing visuospatial tasks and that poor readers show more variability in auditory brain stem responses to speech syllables in comparison with proficient readers (Hornickel & Kraus, 2013). It would be of benefit to address variation in future neuroimaging studies to assess whether patterns of neural activation are consistent among dyslexic individuals. As such, the current meta-analysis advocates for a line of research that seeks to look beyond differences in means and to explore and explain the source of greater variability in dyslexia, but also in a variety of other clinical populations.

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Supplementary information

Supplementary Table 1. Sample demographics, moderator variables and effect size estimates for individual studies included in the meta-analysis.

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Attree et al. (2009)	Block design					-0.41	0.36
	Virtual environment	42	C	Ab	0.79	0.96	0.22
	Recall of designs					-0.82	0.30
Bacon et al. (2013)	Corsi block:						
	Forward					-1.20	-0.35
	Backward					0.35	-0.07
	Forward spatial					0.26	0.01
	Backward spatial	71	A	P	0.37	-0.49	0.03
	Forward visual					-0.19	-0.09
	Backward visual					-0.08	0.001
	Visual patterns test					-0.31	0.12
	Corsi block:						
	Forward spatial					0.27	0.18
	Backward spatial	76	A	P	0.38	-0.12	0.46
	Forward visual					-0.26	0.18
	Backward visual					-0.27	0.46

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Bacon et al. (2013)	Corsi block:						
	Forward					-0.09	0.01
	Backward	138	A	P	0.39	-0.74	-0.36
	Visual patterns test					-1.7	2.11+
Bacon & Handley (2014)	Visual patterns:						
	High load syllogistic					-0.77	0.18
	Low load syllogistic					-0.66	0.31
	High load propositional	60	A	Ab	0.25	-0.62	0.29
	Low load propositional					-0.62	0.22
	Visual patterns test					-0.13	0.27
Bacon & Handley (2010)	Visual patterns test	70	A	Ab	0.30	0.27	0.09
	Visual patterns test	70	A	Ab	0.33	-0.04	0.12
Brunswick et al. (2010)	ROCF Copy					-0.24	0.32
	ROCF Immediate					-0.12	-0.09
	ROCF Delay					-0.08	0.06
	Block design	41	A	P	0.49	-0.24	0.42
	Picture completion					0.45	-0.34
	Ambiguous figures					0.23	0.001
	Virtual environment					0.25	-0.25

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Brunswick et al. (2010)	Object assembly					0.02	0.08
	Incomplete figures					-0.07	-0.19
Godoy de Oliveira et al. (2014)	Block design	62	A	P	na	-0.17	0.47
	Picture completion					0.39	-0.34
	Object assembly					-0.10	0.12
Duranovic et al. (2015)	ROCF Copy	80	C	Ab	0.48	-0.21	0.07
	ROCF Immediate					0.67	0.03
	Vandenberg MRT					0.07	0.13
	Electric grid					-0.24	0.04
	Paper folding					0.73	0.19
	Picture recall					-0.52	0.03
Everatt (1997)	Cube construction	43	na	Ab	na	-0.16	0.16
Everatt et al. (1999)	Cube construction	36	A	Ab	0.56	0.08	0.24
	Vandenberg MRT					-0.05	-0.10
	EFT					-0.56	0.12
Germano et al. (2014)	Visual constancy	66	C	Ab	0.73	-2.61^{+}	0.37
	Visual closure					-2.05	0.10
Gilger et al. (2013)	Vandenberg MRT	15	A	P	0.42	-1.23	0.84

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Helland & Asbjørnsen (2003)	ROCF Copy	33	C	Ab	0.67	0.28	0.05
	ROCF Delay					0.57	-0.16
	Block design					0.18	-0.30
	Picture completion					0.66	-0.11
	Object assembly					-0.09	0.37
	Sequential memory Pictures					-0.22	-0.05
	Sequential memory Symbols					-2.30	0.71
Huestegge et al. (2014)	Visual detail memory Total	42	C	Ab	0.62	-0.29	0
	Visual detail memory Details					-0.63	0
Kaltner & Jansen (2014)	Picture & letter MRT:	28	C	P	0.54		
	Same trials RT					-3.04^{+}	na
	Same trials Error					-0.25*	na
	Diff trials RT					-3.57^{+}	na
	Diff trials Error					-0.28*	na
Karadi et al. (2001)	Egocentric MRT	55	C	Ab	0.42	-0.25	-0.02
Martinelli & Schembri (2015)	EFT	36	C	Ab	1.00	-1.13	0.49
	Sections					-0.06	-0.19
	Jigsaws					0.12	-0.22
	Wallpaper					0.05	-0.05
	Right angles					0.01	-0.02

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Moura et al. (2015)	Corsi block	100	C	P	0.69	-0.29	-0.23
	ROCF Immediate					-0.11	-0.02
Olulade et al. (2012)	Vandenberg MRT RT	15	A	P	0.42	0.63	0.66
	Vandenberg MRT Accuracy					-0.09	-0.01
Rusiak et al. (2007)	Shape MRT	28	A	Ab	0.48	-0.70*	na
	Letter MRT					-1.12*	na
Rüsseler et al. (2005)	EFT Overall	70	C	P	0.51	-0.98	0.06
	EFT Letters					-1.03	-0.22
	EFT Shapes					-0.96	0.46
	Vandenberg MRT					-0.95	-0.38
	Shape MRT					-0.10	0.35
	Letter MRT					-1.21	-0.15
Sigurdardottir et al. (2015)	Cambridge face memory	40	A	Ab	0.40	-1.04*	na
	Vanderbilt holistic					-0.68*	na
Van Doren et al. (2014)	Picture MRT	21	C	Ab	0.44	0.53	0.05
	Letter MRT					-4.88^{+}	0.05
Von Karolyi (2001)	Impossible figures	29	na	Ab	0.62	-0.56*	na
	Celtic matching					0.52*	na
Von Karolyi et al. (2003)	Impossible figures Accuracy	62	na	Ab	0.55	-0.26	-0.16
	Impossible figures RT					0.49	-0.01

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Von Karolyi et al. (2003)	Impossible figures Accuracy	64	na	Ab	na	-0.27	-0.24
	Impossible figures RT					0.54	-1.06+
Winner et al. (2001)	Reference memory					0.75*	na
	Form board					-0.51*	na
	Card rotation	63	na	Ab	0.48	-0.63*	na
	Boats					-1.03*	na
	Vandenberg MRT					-0.85*	na
	Vandenberg MRT	60	na	Ab	0.63	-0.60	0.19
	ROCF Immediate					-1.14	1.01
	Vandenberg MRT Total					-1.16	0.89
	Vandenberg MRT Total/attempted					0.70	0.11
	Spatial word problems					-1.47	0.11
	ROCF Immediate					-0.64	-17
	ROCF Immediate structural	37	na	Ab	0.44	-1.09	0.32
	ROCF Delayed					-0.72	-0.25
	ROCF Delayed structural					-1.65	0.60
Corballis et al. (1985)	Letter MRT	20	na	P	0.90	-0.69*	na
Menghini et al. (2010)	Visual-object learning	125	C	Ab	0.56	-0.64	0.41

Study	Experimental tasks	N	Age	FSIQ	Gender ratio	Glass's Delta	*lnSDR*
Menghini et al. (2010)	Visual-spatial learning					-0.67	0.24
Smith-spark et al. (2003)	Dynamic spatial memory	28	A	Ab	0.58	-0.16	-0.18
	Static spatial memory					-0.61	0.30

Notes: A=Adult; C=Child; P=Present; Ab=Absent; RT= Reaction time; ROCF= Rey Osterrieth Complex Figure; MRT = Mental Rotation Task; EFT =embedded figures task; *SDs unavailable, Cohen's D reported instead of Glass's Delta; + Winsorised value used.